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14. ABSTRACT Ohmic contacts to InAs and InGaAs have been investigated with the objective of providing low contact resistance, good thermal stability, and process compatibility for scaling InP-based heterojunction bipolar transistors to smaller sizes. For p-type InAs, the combination of modest contact resistance and good thermal stability at 250 °C was achieved with metallizations that had thin Pd layers deposited first, followed by W or Ti/Pt barrier layers, then Au. For n-type InAs, however, Pd as a first metal layer provided a higher resistance than conventional Ti/Pt/Au contacts. Ohmic contacts to p-type InGaAs were also investigated. An electron-beam evaporated Pd/Ru/Au contact developed at Penn State provided the minimum resistance of all contacts tested as well as good thermal stability at 250 °C, as demonstrated using contact resistances and cross-sectional transmission electron microscopy. However, Pt/Ti/Pt/Au contacts provided better thermal stability at 350 °C. Due to the possibility of electrochemically preparing Pd/Ru/Au contacts, they were selected for further study, and electroless deposition of successive Pd, Ru and Au layers on InGaAs was investigated.					
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Final Technical Report

Ohmic Contacts for Technology for Frequency Agile Digitally
Synthesized Transmitters

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The Pennsylvania State University

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1. **Abstract** (also appears on SF 298 at end of report): Ohmic contacts to InAs and InGaAs have been investigated with the objective of providing low contact resistance, good thermal stability, and process compatibility for scaling InP-based heterojunction bipolar transistors to smaller sizes. For p-type InAs, the combination of modest contact resistance and good thermal stability at 250 °C was achieved with metallizations that had thin Pd layers deposited first, followed by W or Ti/Pt barrier layers, then Au. For n-type InAs, however, Pd as a first metal layer provided a higher resistance than conventional Ti/Pt/Au contacts. Ohmic contacts to p-type InGaAs were also investigated. An electron-beam evaporated Pd/Ru/Au contact developed at Penn State provided the minimum resistance of all contacts tested as well as good thermal stability at 250 °C, as demonstrated using contact resistances and cross-sectional transmission electron microscopy. However, Pt/Ti/Pt/Au contacts provided better thermal stability at 350 °C. Due to the possibility of electrochemically preparing Pd/Ru/Au contacts, they were selected for further study, and electroless deposition of successive Pd, Ru and Au layers on InGaAs was investigated.
2. **Objectives:** The objective of this program was to investigate ohmic contacts for InP-based heterojunction bipolar transistors and to provide assistance to companies in the DARPA TFAST program that had concerns about the processing or reliability of their contact metallizations.
3. **Status of Effort:** A no-cost extension on this program ended July 31, 2006, but work has continued through a follow-on one-year program. Results obtained after the end of the program are not reported in this document.
4. **Accomplishments/New Findings:** Contacts to n- and p-type InAs and p-type InGaAs were investigated in 2005 and the first part of 2006 for this program.

A variety of pre-metallization surface preparations and contact metallizations were evaluated for p-InAs (Be doped $2 \times 10^{19} \text{ cm}^{-3}$), which was provided by HRL. For preparing the semiconductor surface prior to metal deposition, using buffered oxide etch (BOE) for 60 s provided a lower specific contact resistance than any of the following: $\text{H}_2\text{SO}_4\text{:H}_2\text{O}$ (1:1) for 60 s, $\text{HCl:H}_2\text{O}$ (1:1) for 60 s, or BOE for 60 s followed by a dip in 2.1% $(\text{NH}_4)_2\text{S}_x$. Each contact consisted of three or four layers. The first layer was used to lower the resistance at the metal/semiconductor interface. The middle layer (or pair of layers) acted as a diffusion barrier between the other two layers. The third layer, which was typically gold, was used to lower the metal sheet resistance. Of the first layer metals used (Ti, Pd and Co), Pd showed the lowest specific contact resistance both as-deposited ($2 \times 10^{-6} \text{ Ohm cm}^2$) and after aging at 250 °C for 9 h ($3 \times 10^{-6} \text{ Ohm cm}^2$). The Pd/W/Au and Pd/Ti/Pt/Au contacts showed the best morphology, consuming an average of only 6-7 nm of semiconductor after aging at 250 °C for 9 h.

For n-type InAs, we worked with an epilayer from Rockwell (now Teledyne) and measured specific contact resistances between 9×10^{-8} and 9×10^{-7} Ohm cm^2 , depending on the metallization and surface preparation used. A conventional Ti/Pt/Au (10/50/145 nm) contact provided the lowest contact resistance (9×10^{-8} Ohm cm^2) to the n-type semiconductor whether BOE or HCl were used for surface preparation. Including an ultraviolet (UV) ozone step did not change the measured contact resistance, but adding a dip in 2.1% $(\text{NH}_4)_2\text{S}_x$ increased the contact resistance, contrary to the investigator's earlier work on antimonide-bearing semiconductors. Contacts with Pd and Pt as the first layers provided slightly higher specific contact resistance values ($1\text{-}3 \times 10^{-7}$ Ohm cm^2), while an Er/Pt/Au contact provided the highest specific contact resistance, possibly due to the ease with which Er oxidizes. These contacts were not annealed or aged; tests were performed only on as-prepared contacts.

A significant part of the program was devoted to ohmic contacts to p-type InGaAs, which is the thin semiconductor layer that must be contacted for the base of InP-based heterojunction bipolar transistors. We focused on ohmic contacts with Pd or Pt as the first layer of metallization to obtain a low contact resistance, building upon previous experience with p-type InAs. At the start of this program, we used cross-sectional transmission electron microscopy (TEM) to examine electroplated Pt and Pt/Au ohmic contacts to p-InGaAs prepared at Rockwell (now Teledyne), examining aging conditions slightly more severe than would occur during a dielectric cure or device packaging. We observed an 18 nm thick reaction layer between Pt and InGaAs after annealing for 4 h at 260 °C; however, an InGaAs layer above InP was completely consumed by a thick Pt layer after 12 h at 260 °C. Interestingly, the reaction appeared to stop at the InP layer at this temperature.

Due to depth of reaction of Pd and Pt with InGaAs, we prepared ohmic contacts with thinner layers of Pd and Pt in our laboratory. We initially used electron beam evaporation. Above the Pd and Pt, we used various diffusion barriers and then capped the contacts with Au. The contacts that provided the lowest specific contact resistance of 9×10^{-7} Ohm cm^2 were Pd/Ru/Au (5/20/80 nm). These contacts exhibited good thermal stability at 250 °C for 9 h, consuming only 11 nm of InGaAs, as observed by cross-sectional TEM. More thermally stable and providing a slightly-higher specific contact resistance of 1×10^{-6} Ohm cm^2 were the Pt/Ti/Pt/Au (5/40/40/80 nm) contacts, but they survived aging at 350 °C for 100 h, both maintaining a low resistance and consuming only 15 nm of InGaAs.

To combine the selectivity of electrochemically-prepared contacts with the low resistance and thermal stability of the multi-layer e-beam evaporated contacts that we developed, we also initiated work on electrolessly-deposited Pd/Ru/Au contacts. This contact was chosen over the Pt/Ti/Pt/Au contact since Ti can not be deposited readily electrochemically. Selective contacts are desirable for the base of heterojunction bipolar transistors for use in a self-aligned process, which in turn is favorable for scal-

ing devices to smaller sizes. Compared to ordinary electroplating, however, electroless deposition does not require that an external potential be applied, which may allow more uniform deposition across an entire wafer. Preliminary success with the electroless deposition of Pd/Ru/Au contacts was achieved in the first year of this program with specific contact resistances near 10^{-6} Ohm cm^2 . However, the bath and semiconductor surface preparation chemistries have been adjusted since the time of this program to provide more reproducible layer thicknesses, enhanced thermal stability at 250 °C, and lower contact resistances.

5. Personnel Supported:

Suzanne Mohnney, PI (5% time)
Eric Lysczek, graduate assistant

6. Publications:

1. S. H. Wang, E. M. Lysczek, Bangzhi Liu, J. A. Robinson, and S. E. Mohnney, "Shallow and Thermally Stable Ohmic Contact to p-InAsP," *J. Electrochem. Soc.* **153** 479–482 (2006).
2. E. M. Lysczek, J. A. Robinson, and S. E. Mohnney, "Ohmic Contacts to p-InAs," *Mat. Sci. Eng. B* **134** 44–48 (2006).

7. Interactions/Transitions:

- a. The following presentations contained or were fully based on results from this program:
 1. "Shallow Ohmic Contacts to InAs and Related Alloys for HBTs," Eric Lysczek, Sammy Wang, Joshua Robinson, and Suzanne Mohnney, *TMS Electronic Materials Conference*, Santa Barbara, CA, June 2005.
 2. "Contacts to Semiconductors: From Materials Science Fundamentals to Device Integration," S. E. Mohnney, seminar given at Northrop Grumman Space Technology, Redondo Beach, CA, February 2006.
 3. "Materials for Electronics and Optoelectronics: Metallizations, Novel Semiconductors, and Nanowires," S. E. Mohnney, DARPA/MTO Electronics Symposium (poster presented at the "Future of Electronics" symposium), San Francisco, CA, January 2006.
- b. Consultative and Advisory Functions: The PI provided advice on contact metallizations to the DARPA TFAST program participants NGST (points-of-contact: A. Gutierrez and D. Sawdai) and used cross-sectional TEM to provide feedback on

metallizations prepared at Rockwell (now Teledyne) (point of contact: M. Urteaga). She gave a seminar on electrical contacts at NGST (listed above), and she discussed ohmic contacts for HBTs with M. Urteaga and M. Rodwell (UCSB).

- c. Transitions: Experiments on contact metallizations were performed on epilayers provided by the following DARPA TFAST program participants: Rockwell (now Teledyne) (point-of contact: M. Urteaga), HRL (point-of-contact: D. Chow) and NGST (D. Sawdai). Results obtained using their samples were provided to these program participants prior to publication.